AFOSR-TR-96

0314

Graphics Workstation for Studies of Flows and Flow Control

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May 14, 1996

FINAL REPORT
Air Force Office of Scientific Research
Contract F49620-95-1-0080

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

19960625 172

DTIC QUALITY INSPECTED 1

Abstract

This equipment grant has been utilized to acquire one high-end graphics workstation with two fast processors, adequate memory, disk space, peripherals, and software to adapt the capabilities of our previously existing workstation laboratory to the increasing demand of current research. The workstation is used as compute and file server, for the visualization of large data volumes, and for the development and testing of new software for interactive flow simulations on distributed processors. The equipment has accelerated the progress of our research, enabled the use of interactive visualization techniques to enhance insight into the dynamics of fluid flow, and advanced the development of computational software for high-performance computer architectures.

Contents

1 Overview

This equipment grant has been utilized to acquire one high-end graphics workstation with two fast processors, adequate memory, disk space, peripherals, and software to adapt the capabilities of our previously existing workstation laboratory to the increasing demand of current research. The workstation is used as compute and file server, for the visualization of large data volumes, and for the development and testing of new software for interactive flow simulations on distributed processors. Extensive computations for incompressible boundary layers were performed to support the development of a "smart wall" for active transition control to reduce the drag of aircraft. The results are used as training data for the neural-network controllers, to develop system models for adaptive control, and for the selection of proper sensors and actuators and their arrangement. Computations for compressible boundary layers supported studies of the receptivity, stability, and transition in supersonic flows over realistic geometries. This work focused on the physics of mode interactions and their effects on drag and heat transfer of advanced flight vehicles. Other computations supported the analysis and development of multi-grid methods and the extension of the parabolized stability equations to fully three-dimensional boundary layers. The equipment has accelerated the progress of our research, enabled the use of interactive visualization techniques to enhance insight into the dynamics of fluid flow, and advanced the development of software for high-performance computer architectures.

2 Equipment Description

Supported by research contracts with AFOSR, U.S. Army AMCCOM, and ONR, and an equipment grant from NSF, we have since 1987 established a Workstation Laboratory for Computational Fluid Mechanics and Flow Visualization. The laboratory consists of a variety of SGI Personal Iris 4D/35TG and Indigo workstations with high-resolution 24-bit color, typically 16 or 32 MB memory, and 1 GB disks. Besides the usual peripherals like tapes or laser printers, output of visualizations can be recorded on a Matrix Film Recorder (35mm slides, 16mm film) and a video recording system consisting of a Lyon Lamb ENC7 encoder, VAS Delta animation controller, Sony BVU 950 3/4" video recorder and 13" monitor.

The equipment grant F49620-95-1-0080 has enabled us to upgrade this laboratory in five directions:

1. Computational speed

2. Parallel processing capability

3. Memory

4. Disk space

5. Graphics capability

These upgrades dramatically enhanced our ability to perform large PSE and DNS computations locally and in short turn-around times.

Most of the improvements were achieved by the acquisition of an SGI Power Onyx workstation with two R8000 processors and VTX Graphics. This workstation is equipped with 896 MB of memory and 12 GB of disk space on a Power Channel that executes data transfers without blocking the CPU. Two other Indigo workstations received memory upgrades and additional 4GB disks to enable visualizations of large data sets on additional seats. Licenses for the MP (multi processor) software development tools were obtained to fully utilize the powerful equipment.

The graphics capabilities were enhanced by the acquisition of both hardware and software. Besides an HP 1200C color printer, we acquired an ACCOM 960 frame, 32-second video disk which is utilized for recording of visualization frames. These frames can be replayed on a video monitor or on any of the workstations, and can also be recorded on the video recorder. This video disk with full software support eases the use of video recording substantially. Software licenses for Fieldview, Tecplot, and UIM/X were obtained to enhance the capabilities for flow visualizations, plotting of 2D and 3D data, and the development of graphical user interfaces.

The integration of this new equipment into the previously existing network of workstations has enhanced the overall utility of the laboratory and is much appreciated by the users of the facility. The laboratory is integrated in a network of numerous SGI workstations (mostly SGI Indigo/Indy) in faculty offices in the Mechanical Engineering Department and in the Department for Aeronautics and Astronautics, including one workstation on the low-speed wind tunnel.

The new equipment has made our research essentially independent of the use of supercomputers that imposed a variety of restrictions (memory usage, run time, communication speed, software incompatibility) in previous work. Large runs can be performed in predictable times – a great improvement over remote supercomputing.

3 Effect on Research

The effect of the new equipment on our research has been two-fold: it has enabled conducting the research faster and in a less frustrating pace, and it allowed for an extended scope of the research by relaxing the most severe restrictions. We will illustrate these points using two AFOSR contracts as examples. Two faculty and six graduate research assistants were involved in this work.

3.1 High-Speed Flows over Realistic Geometries

The thrust of this research program has been the improvement of the capabilities for analyzing stability and transition in high-speed flows over realistic bodies. Examples of such bodies are swept wings of high-speed airplanes or the conical bodies for hypersonic flight. We have extended the parabolized stability equations (PSE) for these situations and developed methods for solving these equations in disturbance environments typical of atmospheric conditions. The extension required basic studies on the stability analysis of 3D flows, formulating the equations in general curvilinear coordinates, and developing new formulations for the nonlinear terms in the equations governing highly compressible flows. Proper choices have been made to minimize the effect of the parabolization. In cooperation with DynaFlow, Inc., the method is implemented into a modular code that will replace transition-prediction codes currently used at NASA and in the aerospace industry. A first version of this code for the range of high Mach numbers has been delivered to Wright Laboratories (Herbert et al. 1993a, b).

Accurate transition prediction requires an accurate basic flow for the stability analysis. As a benchmark, we have computed the flow at Mach 8 over a blunt cone with the necessary accuracy using traditional numerical methods to solve the thin-layer Navier-Stokes equations. While the final result was obtained in about 260 hours in multiple runs on a Cray YMP, the total CPU time spent on the result was about three times this amount because failures to converge were not detected before the runs completed. Availability of the final result was delayed by months.

After the code was rearranged for operation on non-vectorizing processors and freed from other provisions for parallel-execution on the Cray, it can produce high-quality basic flows in less time than previously required. With sufficient memory and using single precision, the complete task runs as a background job on two processors practically without overhead.

Major efforts have been spent on characterizing the disturbance environment that determines type and evolution of transition yet is largely unaccessible to direct measurement. For a given basic flow, numerous PSE runs must be performed to determine the variation of the transition location in the multi-dimensional parameter space of initial amplitudes, wavenumbers, and frequencies. Correlation with experimental data permits the selection of parameters typical of flight tests or tests in a specific wind tunnel. The run times have been reduced from several hours on smaller workstations to the range of about ten minutes. A part of this speed-up has been achieved by improving the numerical method. Additional efficiency has been gained by analyzing the data during the computation.

Other parts of this research concern receptivity mechanisms through which disturbances at the boundaries entrain the basic flow. We resumed work on one of

the problems that was previously hampered by insufficient disk space. This study concerns the receptivity of the flow over a leading edge to sound (engine sound) or vibrations which likely cause TS waves. Although this problem is 2D, it requires a large domain and high resolution on the scale of the TS waves. We use a 7th order Hermitian method and a direct solution procedure out of memory. The analysis of the receptivity to sound has made good progress and awaits completion.

Extensive PSE computations were performed to study the nonlinear behavior of crossflow vortices in compressible boundary layers (Herbert & Schrauf 1996). The results explained the failure of the e^N method to predict the transition location in crossflow-dominated cases. These results, and current work to improve the prediction, are important for the wing design by aircraft manufacturers.

3.2 Flow Control with Neural Networks

This research program explores the feasibility of a "smart wall" for the control of transition to reduce the drag of airplane components such as wings, tail fins, or nacelles. This smart wall is envisioned as an array of control units, each consisting of micro-mechanical sensors and actuators, a neural network controller, and an adaptive training algorithm. Ultimately, all components will be integrated in a layer of silicon. Currently, we study two models of control units. The first model is purely computational and serves to design all components. The second model is implemented in a low-speed wind tunnel using conventional pressure sensors and sound-driven membranes as actuators while neural network and training are simulated in an attached computer. This second model serves to validate the computational design procedures and to test hardware components (silicon components in the near future).

The smart wall promises advantages over conventional hybrid laminar flow control systems. Control of the small disturbances that cause transition requires negligible power in comparison to the modification of the mean flow e.g. by suction. The real-time response of neural networks (when built in hardware) provides the fast action required for the active control of unsteady disturbances. Properly designed neural networks have generalization capabilities that provide reasonable responses to untrained situations. On-the-fly training can adapt the control units to varying flight and flow conditions and compensate for the degradation by damage under operational conditions.

In the first phase of the project, we have demonstrated the capability of a single pre-trained control unit to cancel artificial and naturally occurring TS wave packets and prevent the development of a turbulent spot in a certain region downstream (Fan et al. 1993, Haritonidis et al. 1993, Fan et al. 1995, Fan 1995). The training was based on minimal knowledge of the physics: the training data were combinations of a few traveling waves with different TS-like frequencies and wavelengths. The second

phase of the project, however, requires detailed account for the physics. Both the design of actuators and the development of a system model for the adaptive training require the knowledge of the flow response to unsteady boundary conditions. We have modified the multi-grid DNS code of Liu et al. (1993) to study this flow response and to obtain training data for the system model. For small computational domains, we previously performed one run per day on our faster workstations or typically within a few days on the Cray (1.5 hours CPU time, 16 Mwords). Post-processing of the data has been slow because only parts of the unsteady 3D field can be visualized at once.

With our new capabilities to compute, store, retrieve, and archive the visual (color) information we can perform and analyze various runs per day. Using Duhamel integration on pre-computed time series for ramp function actuation, the flow response can be computed with extreme speed and used for the neural network training. Since the training procedure converges within seconds, systematic studies of the numerous parameters provided a data base for optimization of the control unit. This work is currently extended to analyze optimum arrangements of streamwise and spanwise arrays of control units.

Tests of the computer-designed control units in the wind tunnel have shown excellent agreement with the computational model. The tests have confirmed that the control unit can attenuate instability waves in real time and adapt – also in real time – to changing flow conditions. The test results also have raised our confidence in the computational design method. We are at the verge of designing a smart wall for flight testing. The flight tests require cooperation with one of the aircraft manufacturers which still needs to be found.

Besides for direct support of the smart-wall design, we have applied the DNS code for basic research on the wave patterns created by harmonic or pulsed point sources. So far, this work has revealed a strong influence of the geometry of the source on the evolving flow field (Mack & Herbert 1995). This influence is one reason for the confusing disagreements between experiments in different facilities and theoretical results. These results are important for evaluating the results of laminar-flow control experiments that use suction panels. The work is currently continued to analyze the nonlinear interaction of local disturbances and free-stream turbulence.

3.3 Stability of 3D Flows

The strengthening cooperation between university research, high-technology companies, and industry demands application of our basic research results to increasingly complex situations. Approximations introduced to study idealized cases may no longer be appropriate. Therefore, we have directed our efforts toward extension of existing theories and solving the governing equations in more complete forms. This general direction leads to increasing use of computational instead of analytical meth-

ods. The larger volumes of data resulting for realistic problems also require improved access to the information hidden in these data. The new equipment has strongly supported our efforts in this area.

Most laminar flows in realistic configurations such as the flow over turbine blades or the wing of an airplane are three-dimensional, i.e. they depend on three directions in space. In the traditional stability theory, only the variation normal to the surface is retained while the variations in the two directions parallel to the surface are neglected. The "local" analysis is repeated for points along edge streamlines and the evolution of disturbances is patched together by using one of a series of controversial concepts. The development of the PSE has removed one of the approximations: the analysis accounts for the variation of the laminar flow in the streamwise direction. The variation in the third, spanwise direction still must be disregarded, which is valid for 2D geometry (infinite wings or blades) but introduces uncertainty for most realistic geometries.

We have analyzed this problem thoroughly and developed an extension of the linear PSE method where the amplitude functions and the complex phase of the wave functions depend on two variables (instead of one). The computational effort to march the 2D field in the nonlinear fashion required by the PSE method is essentially higher than in the one-dimensional case. While the method has been successfully implemented, the use has been delayed by the unavailability of a suitable basic flow. We currently use a boundary layer code to produce such basic flows for model problems (realistic data available in commercial R&D laboratories are unaccessible/proprietary).

3.4 Multi-Grid, Multi-Domain DNS and LES

As an alternative to the PSE technique, we have worked toward studying the linear and nonlinear stability of 3D flows by DNS. The available multi-grid code (Liu et al. 1993) is not adaptable to these problems. Its use has shown, however, that serious DNS work can be performed on workstations. We have combined our experience in various fields to develop a multi-domain code that uses multi-grid methods to solve the Navier-Stokes equations and other governing equations in different domains. The code implements flexible boundary conditions and is prepared to use general curvilinear coordinates. The code builds on PVM to execute on distributed processors. The new equipment together with the development tools for MP systems has been an enabling part of this effort.

A detailed analysis of the effect of coordinate stretching on the performance of multigrid methods has been performed to obtain guidance for future applications (Briggs 1996).

3.5 Interactive Simulation and Visualization

Directly related to the previous topic is the development and implementation of methods for interactive visualization of the data generated by the DNS code. With proper design at both ends, this software is primarily an interface for data exchange within a single computer or across the network between computers. The visualization software has been derived from the Visual3/pV3 (public domain) codes. With this work we aim at medium size simulations typical of industrial R&D applications.

We have gained previous experience with Cray runs that displayed the graphics across the network on a workstation using the CGL library developed by SGI and NASA Ames. In this mode, the workstation user has no control over the simulation nor over the displayed data. We concluded that interactivity is prerequisite for useful applications of run-time visualization. Although many aspects of our work are in areas such as program design, virtually unrelated to fluid dynamics, we believe that higher-quality computational results and better access to the information are necessary for applying our research results to greater benefit. The new equipment has helped us building a prototype of what we envision as a design tool of the next decade.

4 Effect on Training

The effect on training has been two-fold: directly through the involvement of graduate students in our research program and indirectly through the experience of faculty. The equipment has greatly enhanced the enthusiasm of the graduate students to perform complex computations and visualizations within their research. The true effects on training are difficult to estimate after only one year of usage of the system. It would be highly desirable to prepare students better for the sophisticated use of computers. We have considered teaching a Special Study on interactive computing to propagate our experience in software design for distributed systems. The plans have not been realized because of the high work load on faculty in the current university environment.

5 Personnel Supported

The new equipment supported the work of

Thorwald Herbert, Principal Investigator

Joseph H. Haritonidis, Faculty

Mengjie Wang, Postdoctoral Research Assistant

Xuetong Fan, Graduate Research Assistant (Ph.D.)

Lorenz Hofmann, Graduate Research Assistant (Ph.D.)

Yi-Chung Su, Graduate Research Assistant (Ph.D.)

Robert A. Briggs, Graduate Research Assistant (M.S.)

Eugene Kalinin, Graduate Research Assistant (M.S.)

and others.

6 Publications

The new equipment supported the preparation of one Ph.D. Thesis by X. Fan (see references, item [7]) and one M.S. Thesis by R. A. Briggs (see references, item [10]) as well as work related to a paper by Th. Herbert & G. Schrauf (see references, item [3]).

7 Participation/Presentations at Meetings

Work supported by using the new equipment has been reported in the following presentations:

"Studies on Stability and Transition with Parabolized Stability Equations," by Th. Herbert, Technical University Munich, May 23, 1995

"Evaluation of Transition in Flight Tests Using Nonlinear PSE Analysis," by Th. Herbert and G. Schrauf, Daimler-Benz Aerospace Airbus, Bremen, May 30, 1995.

"Evaluation of Transition in Flight Tests Using Nonlinear PSE Analysis," by G. Schrauf, Th. Herbert, and G. K. Stuckert, 13th AIAA Applied Aerodynamics Conference, San Diego, California, June 19 - 22, 1995.

"Transition Studies in Three-Dimensional Boundary Layers," Invited Lecture, by Th. Herbert, IUTAM Symposium on *Nonlinear Instability and Transition in Three-Dimensional Boundary Layers*, Manchester, UK, 17-20 July 1995.

"Feedback Transition Control with On-the-fly Training of Neural Networks," by X. Fan, J. H. Haritonidis, and Th. Herbert, 48th Meeting of the APS-DFD, Irvine, CA, November 19 - 21, 1995.

"The Status of Applied Transition Analysis," Invited Lecture, by Th. Herbert, Royal Netherlands Academy of Arts and Sciences Colloquium on **Transitional Boundary Layers in Aeronautics; State of the Art and Future Directions of Research**, Amsterdam, Netherlands, December 6-8, 1995.

8 Transitions

Dr. J. D. Crouch, Boeing Commercial Airplane Group, has expressed strong interest by their Computational Fluid Dynamics Lab and the Laminar Flow Control Branch in our development of methods and software to analyze 3D boundary layers. Dr. Crouch specifically addressed the stability problems in those sections of the swept wings where the flow is modified by pylons and engines. These flows cannot be reliably analyzed with current tools, hampering LFC efforts. Unfortunately, the interest in our work is not backed by a funding commitment.

9 Honors/Awards

Thorwald Herbert was elected Fellow of the American Physical Society in 1987. He has been an Associate Fellow of the American Institute of Aeronautics and Astronautics since 1993.

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[4] X. Fan, L. Hofmann, and Th. Herbert. Active flow control with neural networks. AIAA Paper 93-3273, 1993.

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[6] X. Fan, Th. Herbert, and J. H. Haritonidis. Transition control with neural networks. AIAA Paper 95-0674, 1995.

[7] X. Fan. *Laminar Flow Control Models with Neural Networks.* PhD thesis, The Ohio State University, Columbus, Ohio, 1995.

[8] C. Liu, Z. Liu, and McCormick. Multigrid method for flow transition in three-dimensional boundary layers with surface roughness. NASA Contract Report 4540, 1993.

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[10] R. A. Briggs. Applications of multigrid methods on stretched grids. Master's thesis, The Ohio State University, Columbus, Ohio, 1996.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
5/19/96

3. REPORT TYPE AND DATES COVERED
Final 01/01/95 - 12/31/95

4. TITLE AND SUBTITLE
Graphics Workstation for Studies of Flows and Flow Control

5. FUNDING NUMBERS
F49620-95-1-0080

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
110 Duncan Ave., Ste. B-115
Bolling AFB, DC 20332

nm

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS

15. NUMBER OF PAGES
13

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT